



# Evaluation of the effects of irrigation water on groundwater budget by a hydrologic model

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## Abstract

Groundwater is a valuable water resource, and it is used for domestic, industrial or agricultural use around the world. Especially, water use in paddy fields is very large, and it influences groundwater in Japan. However, it is difficult to understand its water balance and to control it for management, because it flows under the ground and is affected by a lot of processes in the hydrologic cycle. Therefore, a hydrologic model, which includes the groundwater system, is required for analysis and management. In this paper, a lumped parametric hydrological model was applied to two different coastal areas to discuss influences of irrigation water use on groundwater. The hydrologic model had good performance in estimating the groundwater level, and it was considered that the model could explain the hydrologic cycle in the areas. Annual water balance in the study area was then calculated using the model to evaluate the effects of irrigation water use on groundwater in each area. The results indicated that (1) percolation to an aquifer consists of infiltration from surface and seepage from rivers. The annual amount of percolation to an aquifer may be more than rainfall in the study area and be equal to several times the total use of groundwater in the areas. (2) However, over-pumping of groundwater in the irrigation season causes lowering of the level and seawater intrusion in one area. On the other hand, decrease in percolation due to reduction in seepage from rivers and infiltration from paddy fields that originated from highly turbid river water is a serious problem in another area.

**Keywords** Groundwater · Water balance · Percolation from paddy fields · Seepage from rivers

## Introduction

Groundwater is a valuable water resource and its management is important not only for the sustainable use of groundwater, but also for conservation of the environment in an area. However, it is very difficult to know how to manage it and we have not yet obtained a good solution in Japan. One explanation for this is a legal reason, in that the right of groundwater use is based on possession of land where the groundwater is below, and another is a scientific reason, in that it is difficult to understand the hydrologic cycle and water balance that includes groundwater. Furthermore, another reason may be that the interests of people in groundwater use and geo-hydraulic properties are quite different from place to place. Therefore, it is necessary to establish a

new legal rule for groundwater management and to develop scientific researches to understand groundwater hydrology.

Hydrologic researches on groundwater are classified into two groups. One is a quantitative approach which includes researches on groundwater flow or budget and another group is a qualitative approach which includes researches on water quality, origin and age of groundwater. Recently, integrated researches have been carried out from a bio-geo-scientific point of view, which focus on the inter-correlation between surface and groundwater (Nakayama 2018). Quantitative approaches are classified into two types. One typical type is a water balance method based on measured or observed data of surface water such as rainfall and rivers. For example, Takase (2000) estimated the recharge to groundwater from the surface region by water balance measurements. Another type is research that analyzes groundwater flow by a model. The MODFLOW model and GWPA model are representative examples. Furthermore, these models are classified into a distributed and a lumped type. Mushiake and Oka (1981) established a lumped parametric model which consisted of tanks to analyze groundwater behavior in a hilly area.

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Recent rapid developments in computer systems enable us to analyze groundwater movement widely and physically by a distributed model, but the application is not so easy because it requires detailed geo-hydraulic information and determination of model parameters. Therefore, we developed a conceptual and lumped parametric model to apply it in two study areas and discuss influences of irrigation water use on groundwater.

## Research area

Two study areas were selected. As shown in Fig. 1, one of them (study area A) is located in Ehime Prefecture in the southwest part of Japan, and the other (study area B) is in Ishikawa Prefecture in the middle northern part. They are alluvial fans and surrounded by mountainous areas and face toward the sea as shown in Fig. 2.

### Study area A

Study area A is situated at latitude 33.9°N and longitude 133.2°E and is in Saijo City of Ehime Prefecture. Kamo River is a main river and it flows in the fan. The alluvial fan is 26 km<sup>2</sup> and annual average precipitation is about 1400 mm with little snow, and air temperature is almost 15 °C. The surrounding mountainous area is 175 km<sup>2</sup>, and it ranges from 120 to 1982 m. Annual precipitation in the mountainous area is two to three times more than that in the lower area. In the alluvial area, some of the river water is taken out from the Kamo River and much of the groundwater is pumped up for irrigation of paddy fields. The groundwater in the area is also used as industrial and domestic water, and the ratios of water amounts for each purpose are 16% for domestic, 8% for industrial and 76% for agricultural use. Water in springs has good quality, and there are a lot of

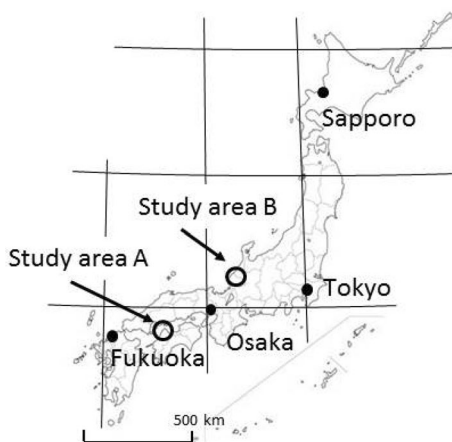


Fig. 1 Location of study area

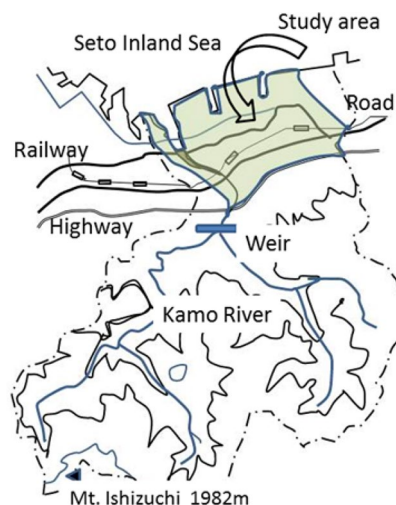


Fig. 2 Location of study area A

wells in the city. However, some problems of lowering and salinization of groundwater have occurred.

Rainfall and meteorological data which were used for the calculation of potential evaporation were collected. Daily discharge from the background mountainous area of the Kamo River was observed at a weir which is located at the top of the alluvial fan. Groundwater level was measured in several wells.

### Study area B

Study area B is situated at latitude 36.5°N and longitude 136.5°E in Ishikawa Prefecture, and it is famous as a rice production area. As shown in Fig. 3, the Tedoru River flows in the alluvial fan and a big irrigation channel network spreads out. The area is 169 km<sup>2</sup> and annual precipitation

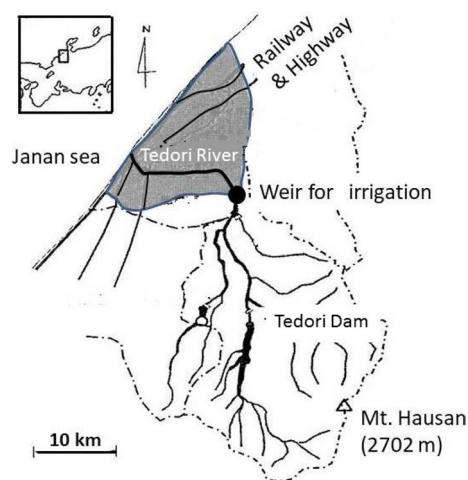


Fig. 3 Location of study area B

is about 2300 mm with much snow in winter. Annual air temperature is about 15 °C. The background mountainous area of the Tedoru River is 733 km<sup>2</sup> and ranges from 200 to 2702 m. Annual precipitation in the mountainous area is three to four times more than that in the lower area. In this study area, most irrigation water is taken from the Tedoru River, and groundwater is used mainly for domestic and industrial purposes, especially for melting snow in winter.

Rainfall and meteorological data were collected for calculation of potential evaporation, and daily discharge data were available at a weir which is located at the top of the fan. Data on the groundwater level were collected at seven wells.

### Modeling of the hydrologic cycle

#### Hydrologic cycle in the area

In both study areas, an important input into the surface region is inflow from the surrounding mountainous area through rivers as well as precipitation in the alluvial area, while outputs are evapotranspiration and outflow to the sea. For the aquifer region, seepage from rivers and percolation from the surface region are major inputs and outputs are pumped water for various purposes and groundwater outflow to the sea. Figure 4 shows a concept of the hydrologic cycle, and a model which is shown in Fig. 5 was developed in this study.

#### Concept of hydrologic model

As shown in Fig. 5, the model that was used in our analysis is a tank model with multilayers and is a lumped parametric type. Fundamental calculation is similar to a normal reservoir model, and it is supposed that the outflow and percolation are calculated by the equations:

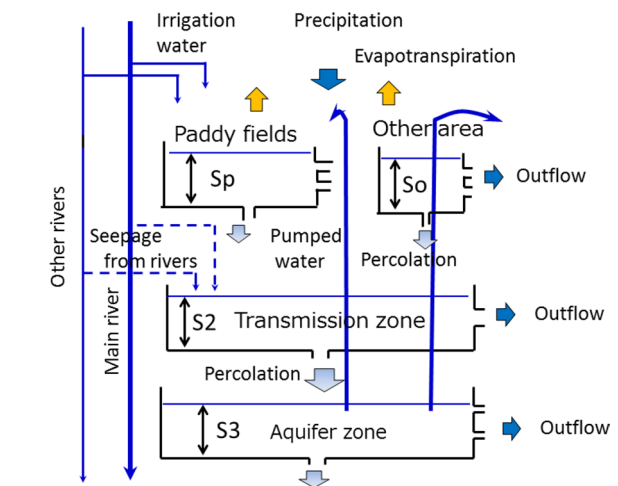


Fig. 5 Concept of hydrologic model

$$q_{out\ i} = a_i(S_i - H_i) \tag{1}$$

$$g_i = b_i S_i \tag{2}$$

$q_{out\ i}$ , outflow from  $i$ th tank;  $a_i$ , coefficient of outflow (parameter);  $S_i$ , water storage in  $i$ th tank;  $H_i$ , height of outflow outlet (parameter);  $g_i$ , percolation from  $i$ th tank to lower tank;  $b_i$ , coefficient of percolation (parameter).

In our lumped model, the surface region is composed of paddy fields and other areas, which includes upland fields, residential areas and so on. Pumped up irrigation water is an input into the paddy field tank and some of the water percolates again. Seepage from rivers flows into the second layer, which means a transmission zone as shown in Fig. 5. It is a key hydrologic process which supplies water to aquifers and it was modeled as follows.

#### Elevation and rate of river water in Kamo River

In study area A, it is well known that the Kamo River supplies much water to groundwater through the seepage of river water, and some relationships between the rate of river flow at the Nagase weir and groundwater level were found as shown in Fig. 6. Therefore, it was supposed that the seepage from a river is proportional to the rate of river flow if the rate is less than a threshold (QU) and the seepage is constant of a maximum amount (QU·CG) if river flow is greater than QU, where the coefficient of seepage (CG) and QU are model parameters which are shown in Fig. 7.

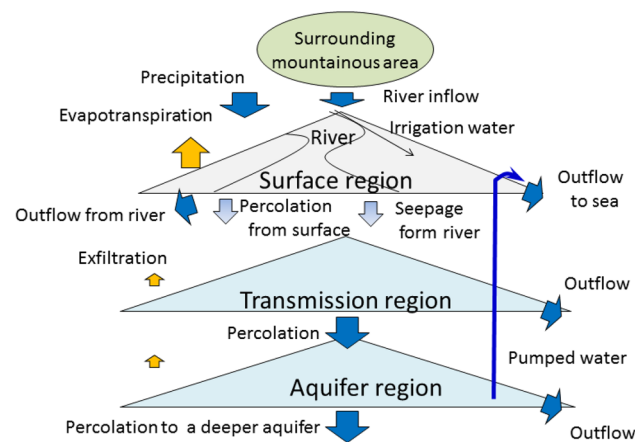


Fig. 4 Concept of hydrologic cycle in study area

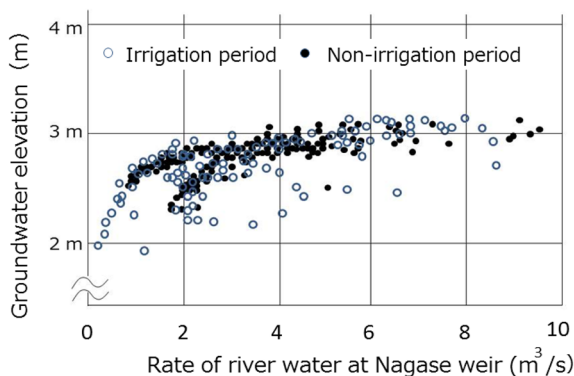


Fig. 6 Relationship between groundwater

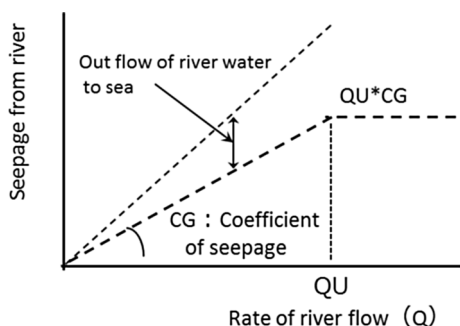


Fig. 7 Sub-model of seepage from river

### Input data for calculation

#### Precipitation

Daily precipitation data at AMeDAS stations were collected in both study areas. In study area A, all precipitation data were treated as rainfall because we had little snow, while a sub-model of snow falling-melting, which had been proposed by us (Takase et al. 2016), was used to distinguish snow and rain in study area B.

#### Actual evapotranspiration

Daily potential evaporation (EP) was calculated by Penman’s equation, using meteorological data at an AMeDAS station and actual evapotranspiration ( $E_t$ ) was obtained by the equation:

$$E_t = EP \cdot f \tag{3}$$

$f$ , evapotranspiration coefficient.

#### Inflow of river discharge from background mountainous area

In study area A, data of river discharge at the Nagase weir on the Kamo River were collected by the prefectural office.

The discharge from other mountainous areas was estimated by multiplying a ratio to the collected data. In study area B, the data were collected at the Nakajima gaging station on the Tedori River by the Japanese ministry, while the river flow from other background areas was estimated by a precipitation runoff model, which had been established by us (Takeshita and Takase 2003), because snow depth in the area was quite different from the Tedori River watershed. An example of discharge data for the Tedori River is shown in Fig. 8. As shown, the discharge in the Tedori River increase from March to May due to snowmelt.

### Irrigation water from river and groundwater

Irrigation water is taken out from rivers and also pumped up from groundwater in study area A. Though it was possible to measure the irrigation water from the Kamo River, it was impossible to know the accurate amount of pumped water because there were too many pump stations in study area A. Therefore, the amount of pumped water was estimated by the equation:

$$PW = ET_{loss} - ER - RW \tag{4}$$

PW, pumped water;  $ET_{loss}$ , consumptive water by evapotranspiration; ER, effective rainfall for irrigation; RW, irrigation water from rivers.

In study area B, most irrigation water is taken out from a main river, the Tedori River, through a big irrigation channel network and the data as shown in Fig. 9 were collected by the irrigation association.

#### Pumped water

In study area A, annual data of pumped water were available for domestic and industrial use but the data for agricultural use were estimated as stated before. In study area B, the annual amount of pumped water was reported by the prefectural office for industrial, domestic, agricultural and snow-melt use. Among these, daily average values of the original data were used for industrial, domestic, and agricultural pumped water. However, it was decided that the snowmelt



Fig. 8 Example of river discharge in study area B

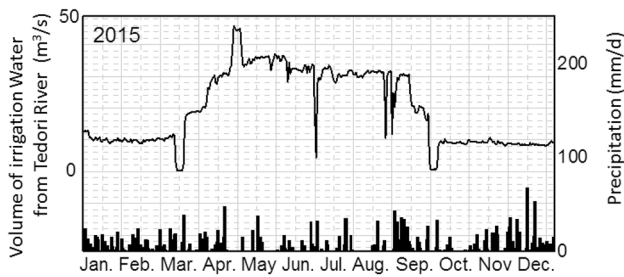


Fig. 9 Example of irrigation water from Tedori River

water might be used only on snow days and the days were estimated by the sub-model of snow falling-melting that was stated before (Takase et al. 2016).

**Groundwater level**

Figure 10 shows an example of daily changes in groundwater elevation at gaging stations in study area A. As stated before, there are several groundwater level gaging stations, but average values of groundwater level are required for our model calculation because the model is a lumped model. In study area A, the arithmetic mean of groundwater levels was adopted because the ranges of fluctuation among gaging stations were almost the same. Furthermore, gaging wells were classified into shallow and deep wells according to the results of principal component analysis. In study area B, the weighted mean was used and the weight for each gaging station was determined by the Thiessen polygon method.

**Results and discussion**

**Performance of model**

The Fortran language was used for the programming and model parameters were optimized so as to minimize total error between daily calculated and measured groundwater

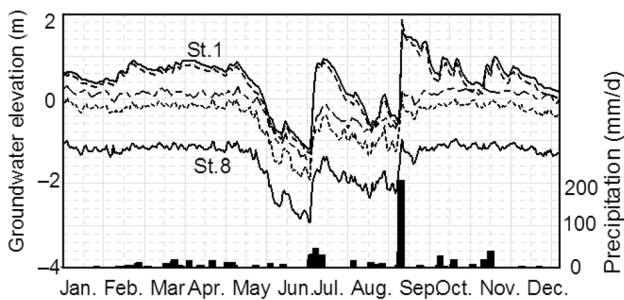


Fig. 10 Example of measured groundwater level in study area A

levels, where the calculated groundwater level (HGc) was defined as:

$$HGc = S/CGE \tag{5}$$

S, storage in an aquifer tank in Fig. 5; CGE, effective porosity of the aquifer.

Then, the following error function was selected for optimization:

$$ERR = \sum_{i=1}^n (HGm_i - HGc_i) \tag{6}$$

HGm<sub>i</sub>, mean value of measured groundwater levels on arbitrary *i*-day; *n*, total days of calculation.

After the model parameters were optimized using daily data for some years, model performance was verified for other years. Figures 11 and 12 show the results of optimization in study area A and B. As shown in these figures, the calculated groundwater levels coincide with the measured values, and it can be concluded that our model represents the actual hydrologic cycle in the study areas. In the verification processes, we have similarly obtained good results in both areas, and it can be concluded that the model is available to analyze water balance in study areas.

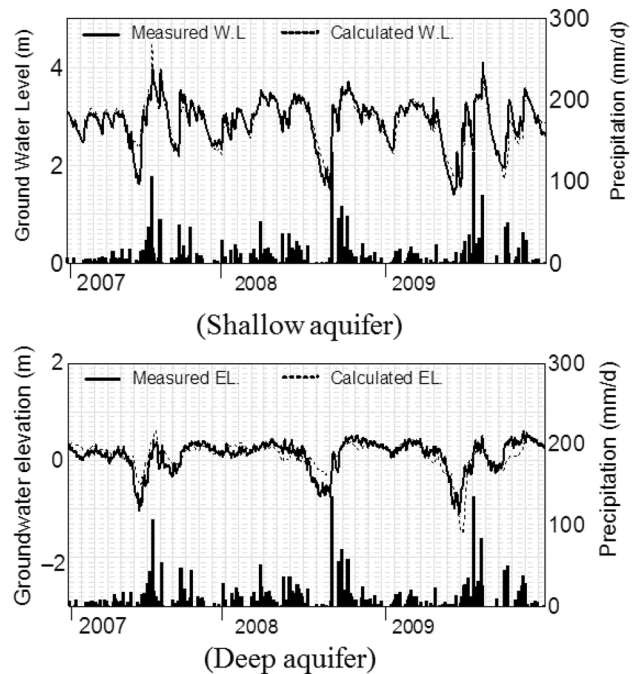
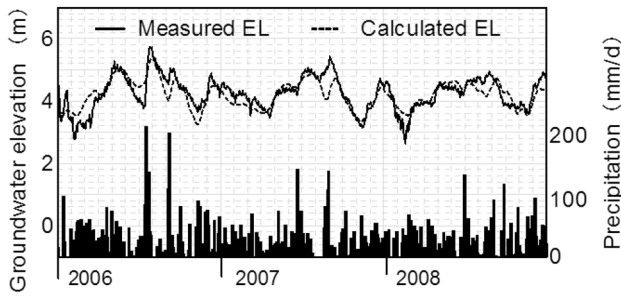


Fig. 11 Comparison of calculated and measured groundwater elevation in study area A



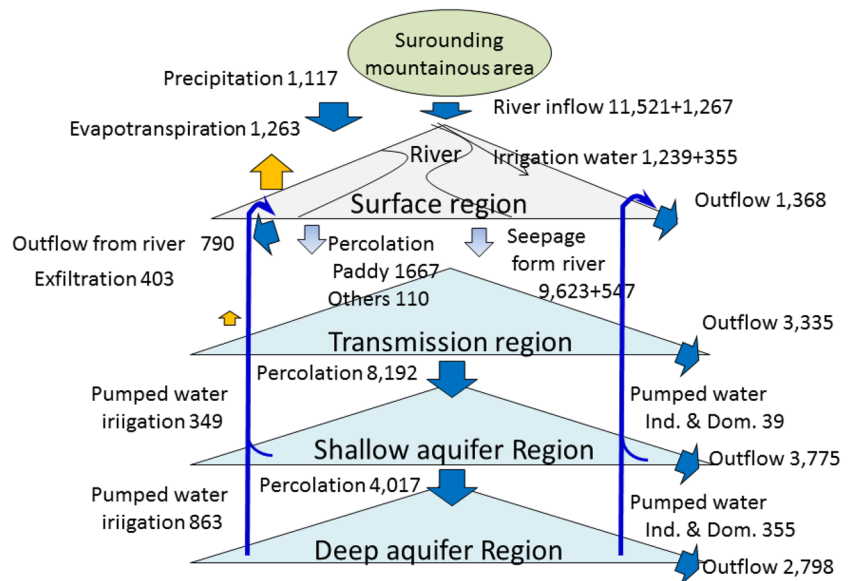
**Fig. 12** Comparison of calculated and measured groundwater elevation in study area B

**Characteristics of water balance in study area**

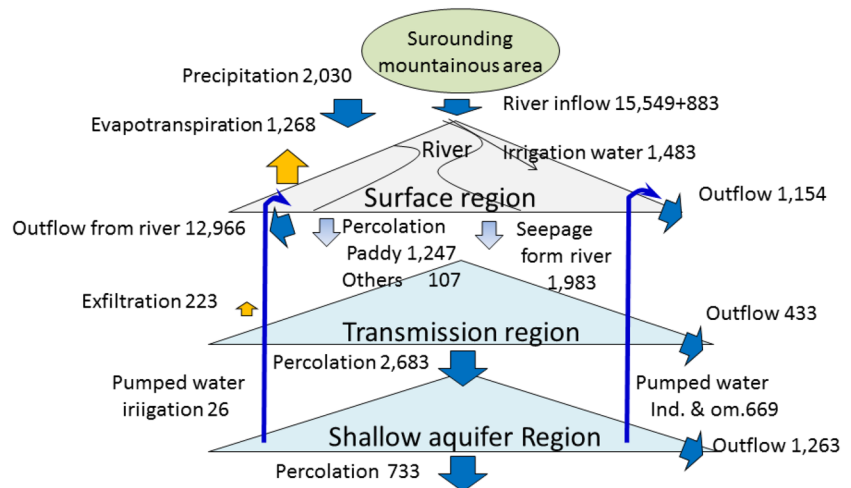
The model with the optimized parameters was used to evaluate the water balance in the study areas. Figures 13 and 14 show the annual water balance in each study area, respectively. Amounts of all hydrologic processes are represented with the unit of equivalent water depth per study area.

In study area A, the total amount of inputs is about 13,900 mm, of which the river inflow from the background mountainous area is 84% and precipitation in the study area is only 16%. The large area (175 km<sup>2</sup>) of the background area and a large amount of annual rainfall in that area provide such ample river inflow. Most of the large amount of river inflow contributes to groundwater through seepage as well as percolation from paddy fields. The amount of seepage from rivers to the transmission zone is estimated to

**Fig. 13** Annual water balance in study area A (2007–2009)



**Fig. 14** Annual water balance in study area B (2006–2008)



be about 10,000 mm, which is almost ten times the annual rainfall in the study area. After the processes of exfiltration and runoff (outflow) from the transmission zone, about 8200 mm of the water is estimated to finally percolate to the shallow aquifer. Most of the percolated water might flow out to the sea as groundwater runoff while some of the water is pumped up for domestic, industrial and agricultural use. The ratio of pumped up water to total percolation is roughly 20%, of which the amount for agricultural use (irrigation) accounts for 75%, as shown in Table 1.

In study area B, the total amount of inputs is about 18,500 mm, which is 1.5 times more than that in study area A because of a large amount of annual precipitation. It is almost similar to study area A in that river inflow from the background mountainous area is 90% of total input due to the large area (733 km<sup>2</sup>) of the background area and large amount of annual rainfall in that area. In this study area, the amount of seepage from rivers to the transmission zone is estimated about 2000 mm, which is almost the same as annual rainfall in the study area. Percolation from paddy fields also contributes to groundwater. After exfiltration and outflow in the transmission zone, the amount of percolation to the aquifer is calculated to be about 2700 mm. It is estimated that half of the percolated water might flow out to sea as groundwater runoff and a quarter might percolate to a lower aquifer. The ratio of pumped up water for domestic, industrial, agricultural and snowmelt purposes to total percolation is roughly 26% and the amount taken up by agricultural use (irrigation) is very small, as shown in Table 1.

### Conclusion and future problems

As discussed above, it is clear that a large amount of water percolates from rivers and paddy fields to aquifers, which enables us to use the groundwater as a plentiful, fresh and healthy water resource in both study areas. However, the water use and water balance related to groundwater are quite different. In study area A, most of the river flow percolates as seepage underground, but the river flow is not as stable because annual rainfall is not very large, so the river dries up on many days in a year. Furthermore, much of the

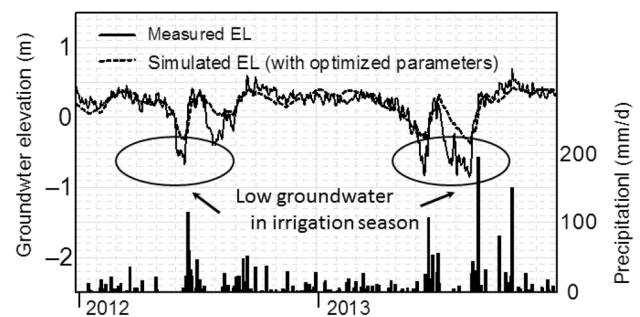
groundwater is used for agricultural use as shown in Fig. 13 and Table 1, especially in coastal areas. As a result, rapid lowering of the groundwater level could be found in the irrigation season with little rainfall, as shown in Fig. 15. A salinization problem of groundwater occurs.

In study area B, most of the river water is allocated to the whole of the paddy fields through a big irrigation network. The irrigation water percolates from the paddy fields and contributes to groundwater as well as the seepage from rivers to groundwater as shown in Fig. 14. However, a big landslide that occurred in the upstream area of the Tedoru River in spring of 2015 has caused many influences on the water environment in the downstream area. Among these influences, turbid river water may be considered to decrease groundwater level. Figure 16 shows a simulation result of groundwater level in study area B before and after the landslide. A great difference between the simulated and observed level is found in this figure and it is surmised that the turbid water may reduce the percolation in paddy fields as well as the seepage in the Tedoru River. This lowering of groundwater had many influences on rare species of fish in fresh water as well as growth of vegetables.

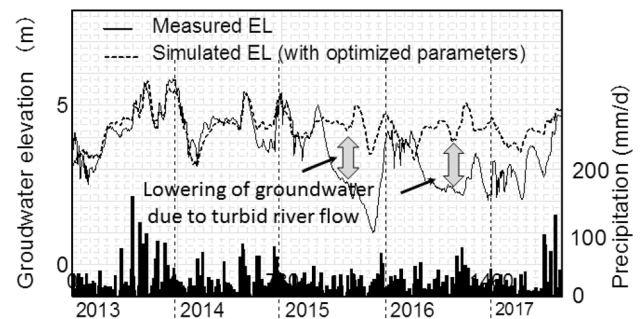
In these areas, some symposiums on groundwater and the water environment have been held. Furthermore, a new plan for management and conservation of the groundwater has been proposed. As a result, many people have been

**Table 1** Ratio of amount of pumped up groundwater for each purpose

	Precipitation (mm/year)	Percentage of pumped up groundwater (%)			
		Agricultural	Domestic	Industrial	Snow melting
Study area A	1117	76	16	8	—
Study area B	2035	4	30	53	13



**Fig. 15** Simulation result of groundwater elevation in study area A (deep aquifer)



**Fig. 16** Simulation result of groundwater elevation in study area B

interested in the hydrologic cycle and water environment. It is important in future for us to understand the hydrologic cycle in their area and to establish new rules for management and conservation of groundwater.

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